Criterion of Wear Resistance for Ranking Steels and Alloys on Mechanical Properties

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Abstract

The new wear resistance criterion based on standard mechanical properties of steels and alloys is proposed. Using this criterion it is possible to conduct the ranking of various steels grades on wear resistance without needing of their tests on wear. Such ranking of steels can be used for various engineering industries and at different stages of technological processes at the creation of machines.

Keywords

Wear Resistance Criterion; Ranking Steels; Mechanical Properties

Introduction

Search of criteria for steels ranking is one of the most important directions of research scientists, not only in Russia but also worldwide. On the basis of these criteria it is possible to choose the best steels on physical and mechanical properties for use their in various kinds of wear and in contact with the abrasive.

The first work in which was the attempt to show the relationship of wear and mechanical properties of steels was the work of M.M. Khruschev. He was one of the first that had obtained the dependence of wear from hardness, but this dependence has always caused the question: why different grades of steels which have equal hardness show varying wear resistance? And wear resistance of pure metals, depending on the hardness are characterized by a straight line.

One can cite a long list of scientists who have devoted many years of his research to tribology. They all are sought to create test methods for wear and to find specific criteria to select the best grades of steels for the conditions of different kinds of wear.

Analyzing the extensive information of research results of other authors, it was possible to draw the conclusion that there are very small the experimental studies on the effect of mechanical properties of steels on wear, and absolutely no survey the full range of mechanical properties that influence on the dependences of various kinds of mechanical wear. For these reasons, the main author's forces had been focused on the study of full range of mechanical properties, on the nature of mechanical wear in all variants of wear [1-4]. In these works a lot of attention was paid to metal science aspects that influence on the nature of wear at sliding friction, impact, in the air flow with abrasive. First of all, it was experimentally proved that the nature of all kinds of mechanical wear has the strength basis and the mechanical wear is a kind of classical destruction of the solid body, with a difference only in the scale factor by the separation of wear particles from the friction surface.

This is the problem which was being studied by authors of this paper for many years. [1-4, 6]. This paper presents the results of research and analysis of experimental data, which allowed proposing a new criterion for evaluating the wear resistance of steels.

Symbols:

WR - wear resistance (g^{-1})

Δm - mass wear (g)

σ_b - ultimate strength (MPa)

$\sigma_{0.2}$ - conventional yield limit (MPa)

ψ - relative reduction of area (%)

δ - relative elongation (%)

HRC - Rockwell hardness

HV - Vickers hardness (MPa)

KCV - impact strength (MJ/m^2)

σ_{-1} - endurance limit (MPa)

a_H - coefficient of impact strength ($kg\ m/cm^2$);

15X, 15 XA, 20X, etc. – Russian grades of steels.

Materials and Methods of Investigations

For the analysis and investigations were chosen the steels belonging to the main structural classes: pearlitic,

austenitic, martensitic, maraging and carbide. Experiments were conducted on the laboratory machine [3, 4] in the mode of sliding friction over the monolithic abrasive.

The methodical feature and difference of this machine from those that were used earlier is that the cylindrical sample is moving radially by its lower face on rotary abrasive wheel plain and is gyrating around of own axle, besides. This is stipulated to eliminate the passage of sample on the friction surface ‘’track in track’’ and thus to avoid the ‘’blocking’’ of working surface of abrasive wheel. Such scheme of trials ensures the higher accuracy and repeatability of tests data from experience to experience. In the experiments were used samples of steels of different structural classes. The wear resistance has been determined as reciprocal value of mass wear—$WR = 1/\Delta m, g^{-1}$.

Apart from steels of different structural classes for which the chemical composition and mechanical characteristics are defined by national standards (GOST) [5], the mechanical characteristics and wear resistance of experimental steels conditionally marked as D4, D5, D6 and D7 also were studied. These steels were created in different time under orders of petroleum industry [6]. The elemental chemical compositions of steels different structural classes used in tests are given in Table 1.

TABLE 1 CHEMICAL COMPOSITION OF TESTED STEELS

Grade of steel	Content of chemical elements, %									
	C	*Si*	*Mn*	*Cr*	*Ni*	*Mo*	*V*	*S u P*	*Co*	*W*	*Ti*
Pearlitic class steels											
45	0.45	0.28	0.70	0.25	0.25	-	-	≤0.04	-	-	-
40	0.40	0.30	0.70	0.25	0.25	-	-	≤0.04	-	-	-
20	0.20	0.30	0.50	0.25	0.25	-	-	≤0.04	-	-	-
D4	0.39	0.28	0.54	0.4	1.1	-	-	-	-	-	-
D6	0.58	0.26	0.55	0.8	1.2	-	-	-	-	-	-
D7	0.7	0.25	0.42	0.6	1.5	-	0.22	-	-	-	-
D5	0.47	0.27	0.69	1	1.4	0.18	0.25	≤0.02	0.25	0.25	0.25
У8	0.8	0.25	0.45	0.20	0.15	-	-	≤0.03	-	-	-
У10	1.0	0.20	0.25	0.20	0.15	-	-	≤0.02	-	-	-
40X13	0.4	0.30	0.65	1.3	≤0.4	-	-	≤0.04	-	-	-
40X	0.4	0.28	0.55	0.9	≤0.4	-	-	≤0.04	-	-	-
Martensitic class steel											
95X18	1.0	≤0.8	≤0.7	18	-	-	-	≤0.03	-	-	-
Maraging class steel											
H18K9M5T	-	-	-	-	18	5	-	-	9	-	1
Austenitic class steel											
110Г13Л	1.1	-	13	1	1	-	-	-	-	-	-
Carbide class steel											
P18	0.8	≤0.4	≤0.4	4.2	≤0.4	0.3	1.2	≤0.03	-	18	-
X12M	1.55	0.25	0.35	12	-	0.5	0.25	≤0.03	-	-	-

Results of Investigation and Discussion

The purpose on the first stage of investigation was the definition of functional bond of steels' wear resistance at the mechanical (abrasive) wear with their standard mechanical characteristics: ultimate strength σ_b, conventional yield limit $\sigma_{0.2}$, endurance limit σ_{-1}, Rockwell hardness *HRC*, relative elongation δ, relative reduction of area ψ and impact strength *KCV*.

The Law Conformity Changing of Strength Characteristics and Wear Resistance from Tempering Temperature of Steels

Almost all standard characteristics of mechanical properties for the possibility of their use as an indicator of steels wear resistance were checked. Analysis of paired relationships of wear resistance with any of one of mechanical properties of steels suggests that the resistance to abrasive wear by the nature of its force action on the friction surface is more complicated than the resistance to direct introduction of indenter at the determination of hardness, and to uniaxial tension - at the determination of tensile strength, yield strength, elongation, and etc.

If the abrasive wear seen as mechanical destruction, we must admit its toughness basis. On the results of experiments [1-4] there are obtained relationships between wear resistance and basic mechanical properties for steels of different structural classes (Fig. 1). You can see the conformity between the variations of strength and wear resistance as a function of tempering temperature for each class of steels.

Changes nature of toughness and wear resistance is one of the same: both of these characteristics are reduced at the increase of tempering temperature. The wear resistance of usual carbon steel (Steel 45) was taken as reference for comparison purposes.

In each class of steels the trend change of indicators for strength and plasticity under heating conditions at the tempering temperatures are not identical.

For example, for pearlitic class steels at the increase of tempering temperature the strength parameters are reduced, and the plasticity characteristics are increased (Fig.1, *a, b*).

For martensitic steels class is the same tendency, like for pearlitic class steels, but decrease of strength characteristics and increase of plastic characteristics are shifted into field of higher tempering temperatures (Fig.1, *c, d*).

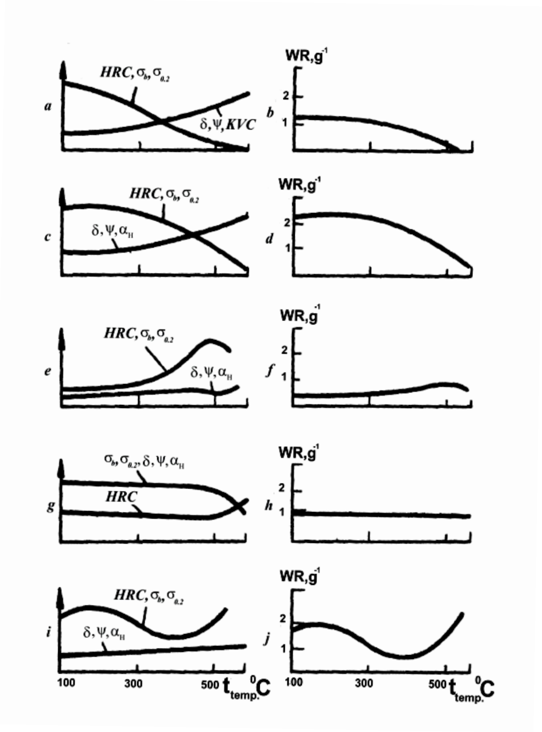


FIG.1 DEPENDENCES OF MAIN MECHANICAL PROPERTIES σ_b, $\sigma_{0.2}$, *HRC*, Δ, ψ, a_H (*a, c, e, g, i*) AND WEAR RESISTANCE *WR*(*b, d, f, h, j*) FOR STEELS OF VARIOUS STRUCTURAL CLASSES FROM TEMPERING TEMPERATURE: *a, b* –STEEL 45 OF PEARLITIC CLASS; *c, d* – 95X18 OF MARTENSITIC CLASS; *e, f* –H18K9M5T OF MARAGING CLASS; *g, h* – 110Г13Л OF AUSTENITIC CLASS; *i, j* – P18 OF CARBIDE CLASS

For maraging steels with increasing tempering temperature until 500 ^{0}C the strength parameters are increased, but at the preservation of high plasticity (Fig.1, *e, f*).

For austenitic class steels at the rising tempering temperature until 400 ^{0}C the strength and plastic indicators do not change, the further rising of tempering temperature leads to decreasing of ultimate strength and plasticity, but the hardness of steels is being raised a little (Fig.1, *g, h*).

For carbide class steels with increasing of tempering temperature the strength parameters are decreased at the beginning, but at the temperature of tempering above than 400 ^{0}C they start to increase, and the plastic characteristics do not change almost (Fig.1, *i, j*).

The results of tribological investigations have allowed to discover the law of conformity between variations of strength characteristics (σ_b, $\sigma_{0.2}$, *HRC*) and wear resistance at different tempering temperatures for hardened steels of all structural classes [1]. These data have allowed concluding that the toughness basis lays in a nature of mechanical wear, but the mechanism of

these processes is more complicated.

There were reasons to consider that at the mechanical wear no one of each possible strength characteristics (σ_b, or $\sigma_{0.2}$, or *HRC)* taken alone cannot be the criterion of wear resistance of steels. Because on the final process of forming and removing of wear particles from the friction surface, apart from strength characteristics, other mechanical properties will influence also. This assumption was confirmed by the analysis of plastic characteristics (ψ, δ, *KCV*) with their strength characteristics [2].

Development of Wear Resistance Criterion

There was repeatedly confirmed experimentally [2] the fact that for equal values of one of steels strength characteristics (σ_b, σ_{02}, *HRC*) were revealed a family of curves differing on wear resistance. So, for example, the wear resistance estimation of several steels grades of different structural classes on the one characteristic of mechanical properties (*HRC*) reveals the complicated dependence (Fig. 2). Its feature is that to one value of any mechanical steels characteristics of different structural classes corresponds to different values of wear resistance.

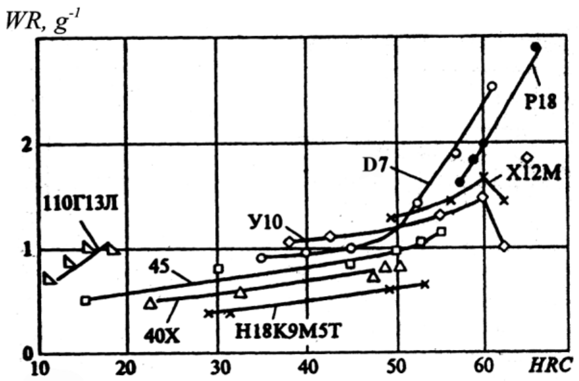


FIG. 2 DEPENDENCE OF WEAR RESISTANCE ***WR*** OF VARIOUS STEEL GRADES FROM HARDNESS ***HRC:*** 1- 110Г13Л; 2 – 45 (BS EN8); 3 – 40X (BS EN8); 4 –H18K9M5T; 5 –У10 (TOOL STEEL); 6 –D7; 7 –X12M; 8 – P18

The investigations of the causes of such differences were prompted by the assumption of existence yet another parameter from the number of mechanical properties which is expressed in an implicit form. Different ways of evaluating the study results of steels wear resistance were tested to prove this hypothesis. Thus, there was arisen the idea to introduce into a number of criterial evaluation characteristics along with parameters of strength and hardness the index of plasticity.

This is the relative reduction of area - ψ that enter to a complex parameter - product of $\sigma_b \cdot \psi$. The handling of steels test results at the abrasive sliding friction on three characteristics – σ_b, *HRC*, ψ gave the respond to the question which was very interesting for researchers: why at the equality of one of strength characteristics, there is formed a family of curves with different wear resistance (see Fig. 3).

Such a problem was decided with applying a new wear resistance definition method which is taking into account simultaneously two properties—the toughness and the plasticity (Fig. 3). The substance of this method consists in mating two functional dependences: ''wear resistance-toughness'' and ''toughness-relative reduction of area''. Then, out of these dependences data, the final parameter in coordinates ''wear resistance-relative reduction of area'' is being defined. This method convincingly has confirmed that in a nature of mechanical wear by sliding friction over an abrasive the leading role belongs to steels' toughness, but the level of strength properties is more significant by higher plasticity.

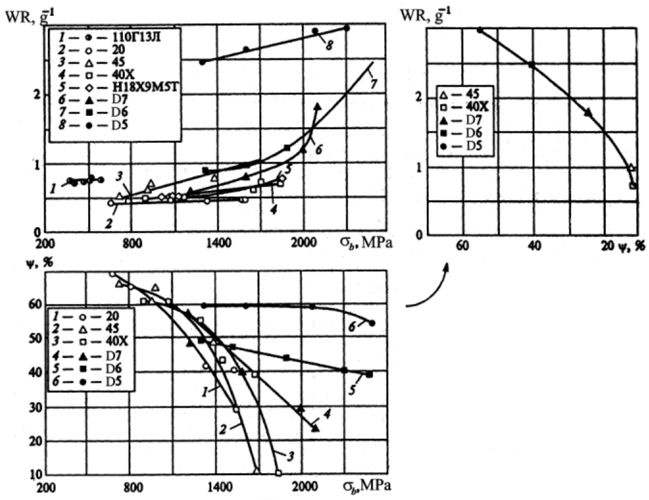


FIG. 3 DEPENDENCE OF WEAR RESISTANCE ***WR*** OF VARIOUS STEEL GRADES FROM ULTIMATE STRENGTH σ_b AND RELATIVE REDUCTION OF AREA ψ: 1 - 110Г13Л; 2 –20; 3 – 45; 4 – 40X; 5 - H18K9M5T; 6 - D7; 7 – D6; 8 –D5

The subsequent studies in this area revealed new difficulties associated with the ability to assess the wear resistance of carbide class steels (P9, P18, P6M5, X12M, etc.). These steels have lesser strength than steels of pearlitic, martensitic and austenitic classes in the conditions of uniaxial tensile. But they superior to all of famous steels on the wear resistance, because of the ability of carbide phase to destroy an abrasive particles, thereby, increasing the wear resistance of steels. It was necessary to search in various versions of criteria the

parameter which could take into account the effect of the carbide phase on wear resistance through the hardness.

As a result, it was found that from combination of multiple mechanical parameters sufficiently reliable estimation of wear resistance can be obtained by means of criterion that takes into account as the product of $\sigma_b{\cdot}\psi$, and hardness HV, i.e. in the form:

$$\sigma_b{\cdot}\psi + HV \qquad (1)$$

This criterion enabled us to explain the advantage of hardening steels by means of carbides, but its main advantage is that it practically ranks (Fig. 4) linearly the steels on the wear resistance and helps to explain this dependence from the metal science positions.

It became apparent that the wear resistance of any steel is determined by three characteristics: tensile strength, hardness and plasticity parameter - the relative reduction of area ψ. This criterion allow concluding definitely that the mechanical wear under abrasive conditions in its nature can be considered as typical destruction, which occurs under the laws identified in the studies of solids destruction [7,8].

The product of ultimate strength on relative reduction of area($\sigma_b{\cdot}\psi$) has appeared universal and permitted to explain not only distinction of steels wear resistance at an equal value of one toughness characteristics, but the difference of endurance strength at an equal value of ultimate strength also (Fig. 5) [2].

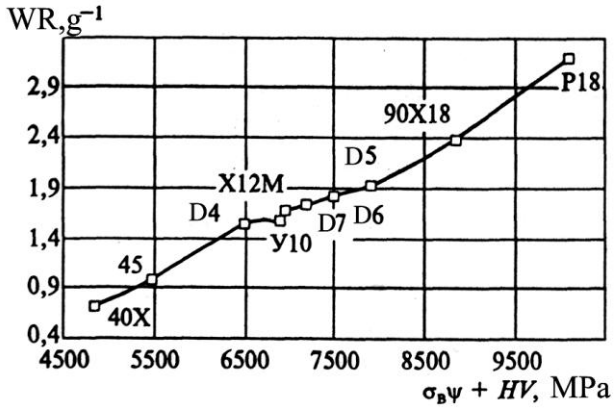


FIG.4 DEPENDENCE OF STEELS WEAR RESISTANCE ***WR*** FROM VARIOUS STRUCTURAL CLASSES AND CRITERION $\sigma_b{\cdot}\psi+HV$

The proposed criterion can be used and for ranking of steels intended for operation under static or long-term loading without wear because its component $\sigma_b{\cdot}\psi$ which is well correlated with the endurance limit σ_{-1} (Fig. 5). Criterion clearly demonstrates an important role of plasticity in all variants of destruction, as well as determining the magnitude of strength properties - tensile strength and hardness.

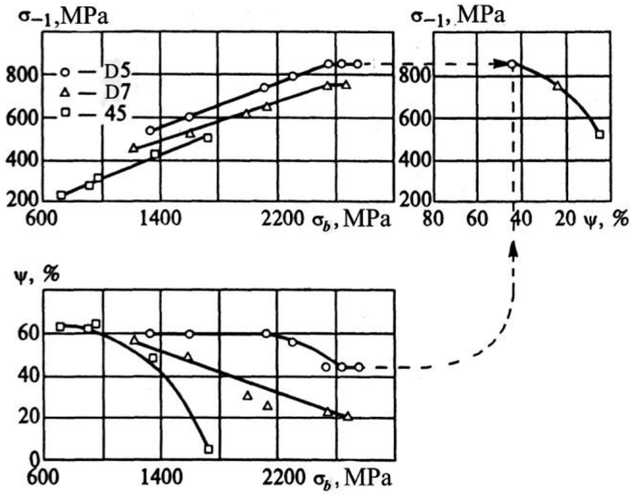


FIG. 5 DEPENDENCE OF ENDURANCE LIMITS σ_{-1} FROM ULTIMATE STRENGTH σ_b AND RELATIVE REDUCTION OF AREA ψ FOR GRADES OF STEELS: 45, D5 AND D7

Ranking of Steels by Using a New Criterion

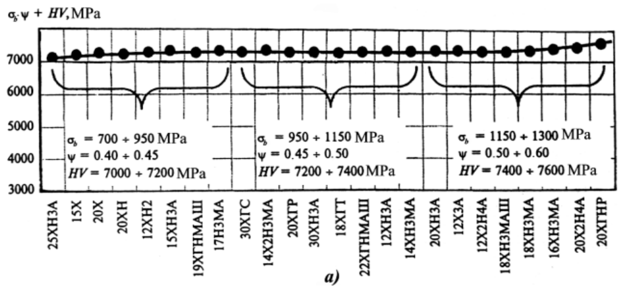
A new criterion for evaluating the mechanical properties of steels can be widely applied in various branches of engineering, to solve various technical problems at different stages of technological processes of machines manufacture, tools, as well as during repair work. Criterion can be used for:

- Determining the suitability of machine building steels on strength parameters for use their at the joint acts of static and long-term loading, including the cases when the steels are in contact with abrasives of various types and under different conditions of interaction of abrasives on working surfaces of machine parts;
- Evaluating of steels strength of different structural classes (pearlitic, martensitic, austenitic, ferritic, carbide), and various technological applications (dies, springs, tools, carburized, not carburized).

This criterion can orient the metallurgists on the selecting the ligatures to ensure high level of strength, hardness and plasticity. It liberates the tribologists from the labor-intensive and long-term tests for wear, which were previously required to assess the wear resistance of steels.

Now using the proposed criterion it is possible to rank all groups of steels which are presented in metallurgical handbook that will allow identify the low-strengthened

steels and remove them from production. This reduction of steels production will improve the durability of the equipment in various industries, which will give a huge economic impact.



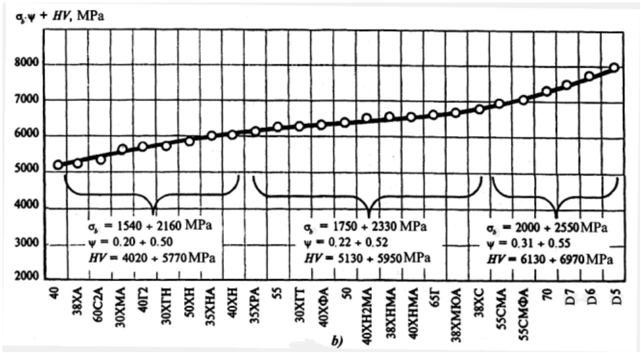


FIG. 6 THE VALUE OF CRITERION ($\sigma_b \cdot \psi + HV$) IN DEPENDENCE OF MECHANICAL PROPERTIES FOR CARBURIZED *a*) AND NOT CARBURIZED *b*) STEELS OF DIFFERENT GRADES

Ranking of steels on their properties will allow identify groups of steels with equal or similar properties and determine the appropriateness of their use. Currently, there are about 30 grades in the group of low-strength, low-alloy and carburized steels, (15Х, 15 ХА, 20Х, 20ХГ, 19ХФ, 15ХР, etc.) with almost identical properties (Fig. 6,*a*). There are 25 grades in the group of low-alloy steels. The properties of most of them on the proposed criterion have slight differences (Fig. 6,*b*). A similar situation is also possible by ranking on this criterion in other steel groups.

In addition, the proposed method of assessing the mechanical properties of steels is able to stimulate the metallurgists to develop steels production with new chemical compositions with possible mechanical properties which can be determined directly in the process of smelting.

The problem of development of the chemical composition of new high-strength steels continues to be relevant. Its feature is the following: at the developing a new steel the authors are based primarily on the existing grade of steel used in this area. The proposed criterion will allow creating the new high-strength steels, focusing on a specific set of desired mechanical properties, which can provide work at higher operating conditions.

Conclusion

The ranking of steels on a complex of mechanical properties determined by proposed criterion (1), allows assessing the quality and quantity of steels used for the manufacture of machines in each industry and expedient to reduce the list of used steels by excluding the low-strength steels which do not meet the proposed criterion. It will streamline not only service of metal science in each industry, but also improve its efficiency.

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